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No. 826.

EXPERIMENTS WITH A NEW MACHINE FOR TESTING MATERIALS BY IMPACT.

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Presented January 5th, 1898.

WITH DISCUSSION.

When stress is applied to a solid body, the material is distorted and a certain amount of work or energy is absorbed. The work thus absorbed in the deformation of the material is called resilience. If the stress changes from zero up to the elastic limit of the material, the energy absorbed during the change is the "elastic resilience" of the material. If the stress changes from zero up to the ultimate strength of the body, the energy absorbed is the "ultimate resilience" of the body.*

In the study of this subject it must be borne in mind that resilience is work, and hence depends upon two essential factors, force and distance acted through. The latter is fully as important as the former. The word toughness, as used by engineers, is synonymous with resilience. In fact, the latter may be defined by saying that resilience is toughness reduced to measurement.

* This use of the word resilience will be objected to by some as not being in conformity with the original meaning of the word. It is sanctioned, however, by some authorities (see Thurston's "Materials of Engineering"), and, for want of a good substitute, may be considered as a technical term.

Having defined resilience, it is next found that, as it depends upon change of stress, different results may be looked for when the stress is applied suddenly, from those obtained when it is applied slowly. The resilience under impact may not be the same as the resilience under gradual load. In this connection impact should not be confused with sudden load. The effect on resilience of rapidity of change in stress can only be determined by actual experiment. This is especially true in the case of material not perfectly elastic, or where the stress has passed the elastic limit of the material.

Again, the resilience of solids may be studied under the four principal kinds of stress, viz., tension, compression, torsion and bending. The relative resilience under these different forms of stress can only be determined by experiment. A knowledge of the resilience of materials of construction is of the greatest importance to the engineer. It is the great resilience of the battle ship's steel armor that enables it to withstand the impact of heavy projectiles without destruction. It is the low resilience of cast iron that makes it so inferior for railway bridges. It is on account of the high resilience of wood that it cannot, in many cases, be supplanted by masonry, glass or other decay-proof material. A concrete railroad tie cannot take the place of the oak tie because it lacks resilience.

Admitting the importance of a knowledge of resilience, a brief consideration of the difficulties to be overcome in obtaining such knowledge is naturally next in order. It is at once found that they are of considerable proportions. To find the strength of a beam under given conditions it is only necessary to find its weakest section and study that. To find the resilience of the beam all sections must be taken into account. If the beam is irregular in form, the problem becomes quite a difficult one. If the final stress exceeds the elastic strength of the material, the difficulties are increased.

The actual measurement of the resilience of a beam has been found quite difficult. The load must be increased gradually and the deflection measured and recorded with its corresponding load. As the breaking point is neared the difficulties of accurate work become important, especially in the more ductile materials. If the determination of the resilience by impact or drop test is attempted, other complications arise. The mass or weight of the beam itself now becomes a factor in the test. The work absorbed by the anvil

and hammer and that taken up in abrasion, etc., are difficult to estimate.

To one who has a proper understanding of these difficulties in measuring resilience, it is not surprising that the subject is somewhat neglected in the studies of practical men. At present it may be said that the knowledge of comparative resilience of materials is "appreciable, but not describable." It is known that a cubic inch of oak has more resilience than a cubic inch of white pine, but the value of either cannot be expressed in inch-pounds or foot-pounds. What is known about resilience, and the modern methods of determining its value, will be briefly considered.

An interesting series of experiments on the resilience of beams under impact was made by Mr. Hodgkinson. The following quotations from a book well known to engineers* will show the more important results of these experiments:

"The power of a beam to resist impact is the same at whatever part of the length it is struck; * * * this remarkable result has been confirmed by experiment."

"In rectangular beams of unequal dimensions the resistance† is the same, whether the bar is struck on the narrow or broad dimension."

"With rectangular beams the resistance to impact R is simply proportional to the weight of the beam between supports, irrespective of the particular dimensions."

The above laws exclude the effect of inertia.

"Mr. Hodgkinson has shown by his experiments that in resisting impact, the power of a heavy beam is to that of a light one as the inertia of the beam, plus the falling weight, is to the falling weight alone, or as $\frac{I + W}{W}$."

"I is the inertia of the beam and the load upon it."

"The inertia of a beam, uniform in cross-section from end to end, supported at the ends and struck in the center, may be taken at half the weight between supports. * * * To this has to be added the whole central load, if any."

In the second column of Table No. 20 will be found some values for the resilience of certain materials, which were obtained from the book above referred to.‡ In modern practice, the testing of mate-

* "Strength of Materials" by Thos. Box.

† Resilience?

‡ Interesting matter on the subject of impact, resilience, etc., will be found in *Engineering News*, August 2d, 1894. See also "A Photographic Impact Testing Machine" with discussion, *Journal of the Franklin Institute*, November, 1897, and January, 1898.

rials by impact is by no means uncommon. Such tests, however, are generally made on the finished shape, as in the case of railway axles. In a code for testing materials, recommended by a committee to the American Society of Mechanical Engineers,* it was prescribed that drop tests should be made with a steel ball, weighing 1 000 to 2 000 lbs., having a clear fall of 20 ft. The anvil, block, frame, etc., should weigh not less than ten times as much as the ball. Drop tests were recommended for rails, tires and axles. Again, the Master Car Builders' Committee,† have recommended drop tests for railway axles. These tests were to be made with a tup, weighing 1 640 lbs. The anvil should weigh 17 500 lbs., and should rest on springs. The axle should rest on supports 3 ft. apart. Cast-steel drawbars are now regularly furnished by contract, under specifications which call for drop tests of sample drawbars, specifying weight of tup, height of drop and number of blows. Drop tests of steel rails have been in practical use for many years.

Besides the above tests of finished shapes, the following methods, which are used in commercial practice, may be noted. These tests, while they do not measure the resilience so directly, are, nevertheless, intended to prove the toughness of the material.

In testing cast-iron water pipe by hydraulic pressure, it is customary to strike the pipe smartly with a hand hammer while the pressure is on. In inspecting steel where a sample bar is nicked and then bent with the hammer, the behavior of the bar indicates the degree of toughness which the material will have under impact. A high percentage of phosphorus in steel is believed to reduce its ability to withstand shocks, while its strength and percentage of elongation remain unchanged.‡ So that it may be said that the specified chemical determinations of phosphorus in structural steel, which are now in use, are really indirect tests of resilience under impact.

Users of structural steel will readily see the necessity which now exists for a definite physical test for the ultimate resilience of steel under impact. It was this special necessity which led the author into the study of the subject, and suggested the experiments described in this paper.

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* See *Engineering News*, March 7th, 1891.

† See *Railroad Gazette*, June 26th, 1896.

‡ See Johnson's "Materials of Construction," pages 166 and 167.

PLATE XII.
TRANS. AM. SOC. CIV. ENGRS.
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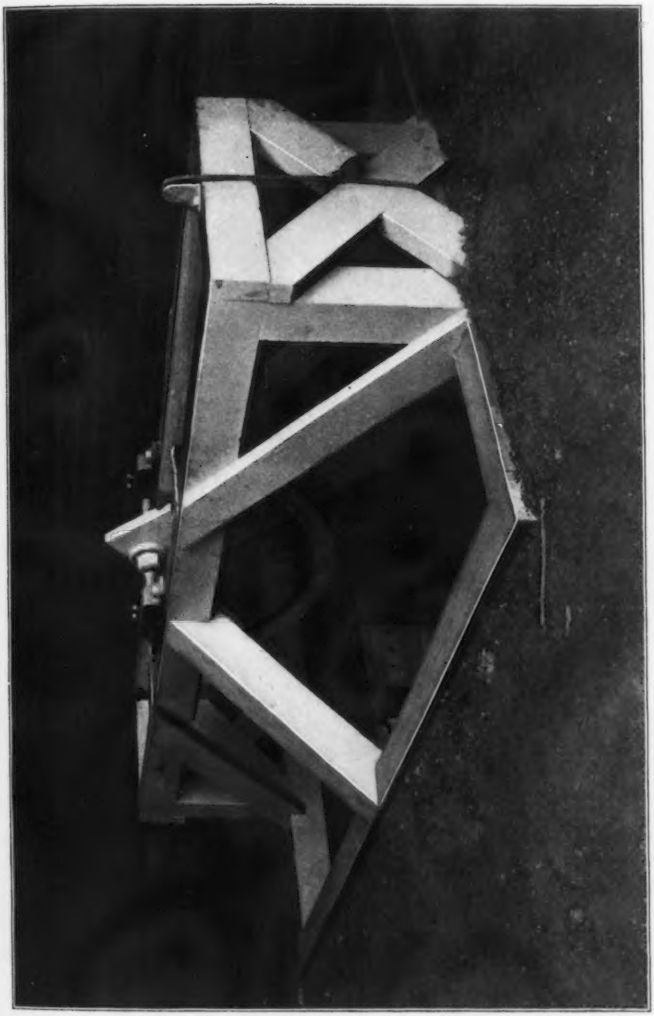
RUSSELL ON IMPACT TESTING EXPERIMENTS.



If, instead of limiting the percentage of phosphorus in the steel, a certain ultimate resilience per cubic inch of the metal, when tested by impact, could be called for, a step would be made in advance. If a definite resilience under impact could be specified, just as a definite strength and ductility are now called for, the proper inspection of steel would be much more simple and satisfactory.

The difficulties of making impact tests have already been suggested. Some machines which have been used for making such tests are of a type greatly open to criticism. For example: In some machines the supporting parts are either so light or so yielding that an important part of the energy of the blow is absorbed by them, and the test piece appears to sustain a much heavier blow than it would in fact on the proper rigid supports.

Two general forms of testing machine have been used in recorded tests. In Mr. Hodgkinson's experiments the hammer used was in the form of a pendulum striking with a horizontal blow. The weight of the hammer was concentrated in the head or ball, and the effect of the rod or radius arm was probably neglected. The most common form of impact testing machine is doubtless the heavy weight falling vertically, somewhat after the fashion of the common pile-driver. In none of these machines is there any means for measuring how much energy is left in the hammer after breaking the piece.

The Impact Testing Machine.

The machine used in making the experiments given herewith was devised by the author and has some special features.

In designing it the main idea was to make a machine which would measure the energy actually absorbed in breaking the test bar. This was to be done by using a hammer in the form of a pendulum, and so arranged that it would strike a horizontal blow, breaking clear through the bar and swinging freely up to the height due to the velocity after the impact. The difference between the height through which the hammer fell before striking, and the height to which it rose after striking, would measure the energy absorbed in breaking the bar. The test piece would rest against two vertical knife-edges and be struck in the middle by the falling pendulum, thus giving the ultimate resilience of the bar under transverse stress.

In developing this idea it was found best to make the pendulum or hammer of the very simplest form, so that the center of percussion and center of gravity could be definitely computed.* The hammer adopted was a rectangular steel bar pierced by a shaft at the upper end and provided with a suitable striking edge near the lower end.

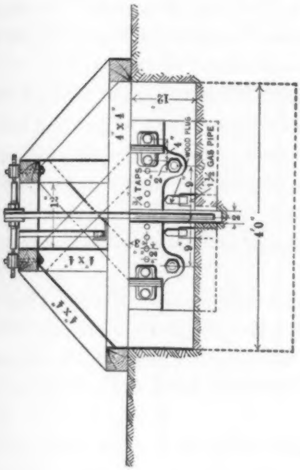
Figs. 1, 2 and 3 show the form and dimensions of the machine used in the experiments. Plate XII is from a photograph which shows somewhat imperfectly the general appearance of the apparatus. The hammer used weighed 103 lbs. The fixed knife-edges were designed so as to allow the broken bar to swing out of the way of the moving hammer, and were secured in a manner which allowed them to be adjusted for spans of 8, 12, 16, 20 and 24 ins. The heavy anvil plates behind them were bolted to a large anvil block of concrete which was sunk in the earth. Adjustable supports were provided to hold the test bar in position with the axis of the bar opposite the center of percussion. The pivot blocks which support the hammer shaft are adjustable to allow for test bars of different depths. Attached to the hammer shaft is a registering device on which the swing of the hammer is read. The pivot blocks, etc., are supported by a strong wooden frame. Attachments are provided for raising and releasing the hammer. The plans for this machine were made in May, 1896. In making the design, the author was assisted by Mr. William F. Schaefer and Mr. Vernon Baker.

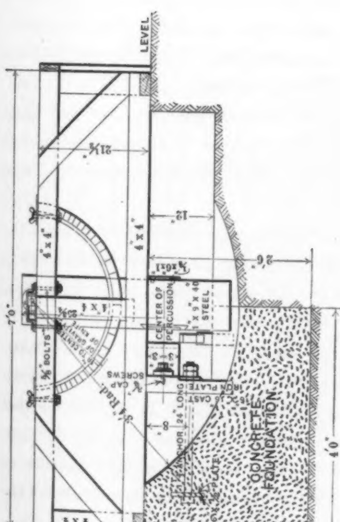
Figs. 4, 5 and 6 show the plans and Fig. 12 the details of a later design which it is thought embodies some improvements in detail, although the essential features are the same. In this design the frame will be of iron and the operator will have more room in which to work while setting the test bars in place.

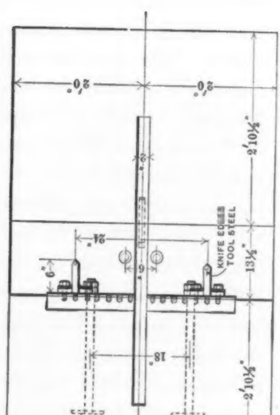
In using the testing machine the first point that comes up is the loss due to friction of the hammer in its bearings. In practice it was found best to determine the friction anew for each set of experiments. If the bar was to be given a blow of 6 ins., the friction loss was determined for a fall of 6 ins. If the hammer rose 2 ins. after breaking the bar, the friction loss for a fall of 2 ins. was determined by trial. The average of the two values was called the correction for friction.

To test the rigidity of the knife-edges and their supports, a nickel 5-cent piece was placed on edge on the top end of one of the knife-

*The formula for finding the center of percussion will be found in Rankine's *Applied Mechanics*, Art. 581.







Figures 1, 2 and 3.

edges. A cast-iron test bar 2 ins. by 1 in. was then broken by a single blow. This experiment was repeated a number of times, and, in the majority of cases, the coin was not overturned by the shock.

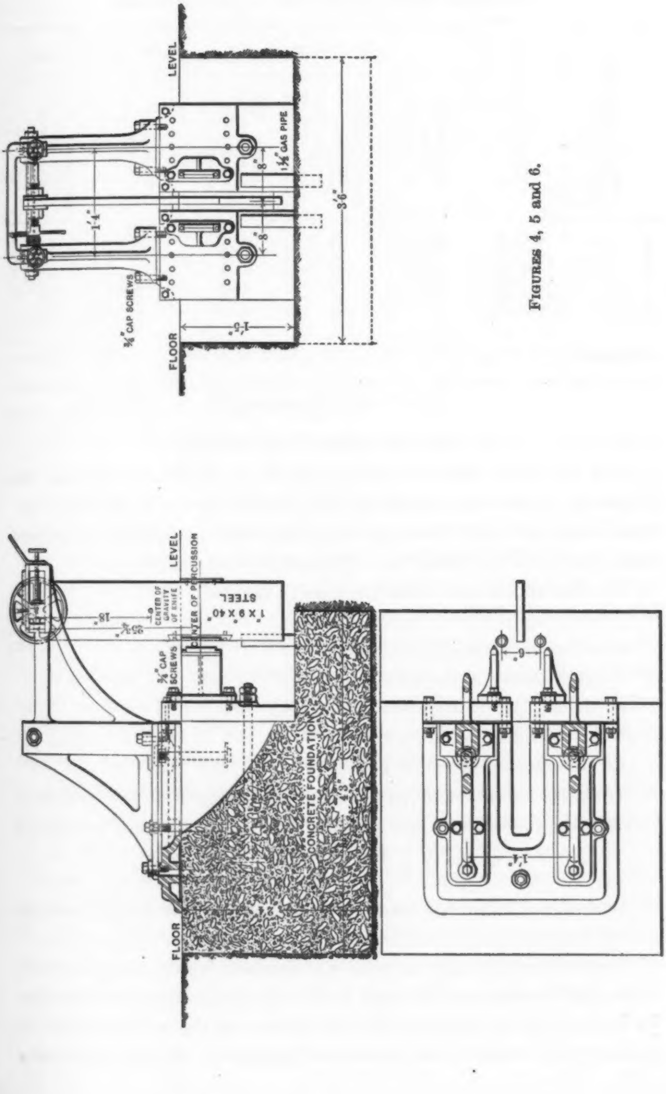
An effort was then made to measure the movement of the knife-edge under a heavy blow. The movement was found to be so small that in the case of a cast-iron test bar, the energy absorbed by the yielding of the knife-edges would be quite inconsiderable. Every impact testing machine should be tested in this way, to see if any considerable percentage of the energy is absorbed by the yielding of parts that support the test piece.

In this method of testing materials some energy is absorbed in overcoming the inertia of the bar itself. The proportionate amount of this energy is probably dependent on the weight of the test bar compared with the weight of the hammer, and also upon the velocity of the hammer.

Owing to the difficulties of ascertaining how much energy is absorbed in this way, it is best to use a test-bar whose weight is small in comparison to that of the hammer. In this way the error due to inertia of the test piece can be reduced, if not eliminated.

In Table No. 5 will be found the results of tests made to determine the effect of changing the initial fall of the hammer. The results are somewhat contradictory, but, in a general way, it may be said that the experiments indicate that a small change in the initial fall of the hammer will not change the amount of energy absorbed, to any great degree. This conclusion may be regarded as important, as upon it depends somewhat the interpretation of all the experiments. Table No. 5 will be referred to again.

The machine having been described, it only remains to present the experiments themselves. Over 700 specimens have been broken, up to the present writing. These tests are not all recorded here; only those which were thought to be most instructive are given. In order to learn the possibilities of the testing machine, the study of each material was continued only until it was thought that the principal difficulties peculiar to such material had been overcome. It is obvious that the resilience values obtained for different materials cannot be taken as final, and should only be used by the designer in the absence of more accurate determinations. All the experiments were made by the author, with the assistance of Mr. William F. Schaefer.



FIGURES 4, 5 and 6.

TABLE No. 1.—Resilience by Impact and by Gradual Load.
Cast-iron bars 1 in. by 2 ins., broken flatwise.

Lot or Melt Nos.	Experiment Nos.	By Impact.			By Gradual Load.	
		Number of tests.	Length between supports, in inches, L.	Resilience per cubic inch, in inch-pounds. R_1.	Number of tests.	Resilience per cubic inch, in inch-pounds. R_0.
1	125–130	6	24	11.5	3	9.0
2	137–139	3	24	10.8	3	8.7
3	156–159	4	24	11.4	3	8.5
4	219–222	4	24	11.8	3	8.8
6	391–393	3	12	17.9	2*	11.1
7	448–449	2	12	14.8	2*	8.2
Averages				13.08		9.05

* $L = 24$ ins. with gradual load.

Tests of Brittle Materials.

The first tests were made with cast iron. Table No. 1 shows the resilience of cast-iron bars tested both by impact and by gradual load. Each value given is the average of several tests. In making the impact tests, the following values are obtained by observation:

F = the initial fall of the hammer in inches.

S = the rise after the blow in inches.

C_1 = the correction for friction.

L = the distance between supports.

h = the depth of beam.

b = the width of beam.

All dimensions are in inches.

Then, by computation, when 103 is the weight of the hammer in pounds, the resilience in inch-pounds per cubic inch of the material, or

$$R_1 = \frac{103\,[F - (S + C_1)]}{L\,h\,b}$$

Table No. 19 shows a series of observations just as they were recorded by the observer, and extended in the office.

The resilience by gradual load was obtained by breaking the bar in a standard testing machine and accurately measuring the deflections up to the point of rupture. The resilience was then taken as half the product of the load by the maximum deflection. The true resilience,

TABLE No. 2.—RESILIENCE FOR DIFFERENT SPANS.

Cast-iron bars, 1 in. by 2 ins., broken flatwise.

Lot No.	Experiment Nos.	24-IN. SPAN. Number of tests.	24-IN. SPAN. Resilience per cubic inch, in inch-pounds. R_1.	12-IN. SPAN. Experiment Nos.	12-IN. SPAN. Number of tests.	12-IN. SPAN. Resilience per cubic inch, in inch-pounds. R_1.
1..........	125–130	6	11.5	131–136	6	11.7
2..........	137–140	3	11.0	146–155	10	11.0
3..........	156–159	4	11.4	170–174	5	12.7
5..........	296–299	4	9.9	300–303	4	10.2

as obtained by a strain diagram, would be slightly greater than this, but the error is not important as the strain diagram for cast-iron is nearly straight to the point of rupture.

Returning to Table No. 1 and comparing the resilience by impact and by gradual load, it will be seen that the former exceeds the latter more than 40 per cent. This difference is so great that it can hardly be accounted for by losses due to inertia of bar, indentation, or movement in supports. The bar is light compared with the hammer, so that not more than 7% could be lost by inertia according to Mr. Hodgkinson's rule. The supports are so rigid that not more than 1% could be lost by their movement. The indentation is so slight as to be inconsiderable when compared with the deflection of the bar, hence there can be no great loss in this way. The logical conclusion is that more energy is absorbed in the sudden rupture of a bar than is the case with rupture under a gradual increase of load.

It has occurred to the author, that perhaps the causes of this difference may be traced back to the heat which is liberated under change of stress. Under gradual increase of stress the heat liberated has time to be conducted away from the distorted fibers. In the case of sudden rupture, the heat has no time to escape and must produce a rise in temperature. If this be admitted, it seems not impossible that the resilience may be affected by the rise in temperature of the distorted particles. This suggestion should be taken for what it may prove to be worth.

Table No. 2 needs no explanation. Bars of the same melt, but of different spans, are compared. A bar of 12-in. span has twice the

TABLE No. 3.—Resilience of Cast-Iron Bars.

Cross-section, 1 in. by 2 ins. Span, 24 ins. Melt No. 2.

Position.	Experiment Nos.	Number of tests.	Resilience per cubic inch in inch-pounds. R_1.
Flatwise	137–139	3	10.8
Edgewise	140–143	4	9.1
Average			9.95

strength and one-quarter the deflection of a bar 24 ins. in span. With the former, then, a greater loss of energy by movement of the knife-edges and by indentation might be expected. Theoretically, the error from these sources would be about eight times as great for the shorter span. On the other hand, the error from inertia should be about twice as great in the longer span as in the shorter one. It will be seen by the table that the difference in the resilience per cubic inch ranges in value from nothing up to about 10%, and that the shorter span shows the higher average resilience. It is fair to conclude from these experiments, as far as they go, that the ultimate resilience of a bar of cast-iron is proportional to its volume and is independent of the span.

Table No. 3 shows that a flat bar has about the same resilience whether broken flatwise or edgewise. All these bars were cast from the same melt. In the case of a bar 2 ins. wide and 1 in. thick, it should have, when broken edgewise, twice the strength and half the maximum deflection that it would have flatwise. The error from yielding supports and from indentation should be about four times as great in the former position. The error from inertia of bar should be the same in both cases. It would be expected that the bars would show greater resilience when broken edgewise. The observed resilience was, however, somewhat greater in the average, with the bars broken flatwise.

As in testing bars in this manner, it is possible for the experimenter to raise the hammer considerably higher than is necessary to break the bar, the question naturally comes up: Will the height to which the hammer is raised affect the results obtained? A number of experiments were made to decide this point, and the results are recorded in Table No. 5. The experiments were made in this manner: Twelve to sixteen bars were taken from the same melt of cast-iron.

TABLE No. 4.—Resilience of Cast-Iron Bars.

Effect of planing. Melt No. 4.

	Experiment Nos.	Number of tests.	Span in inches L.	Depth of beam in inches, h.	Width of beam in inches, b.	Weight of bar in pounds, W.	Resilience per cubic inch in inch-pounds, R_1.
Rough..........	215–226	12	24	1	2	13	11.6
Planed..........	253–263	11	12	0.91	1.93	5.7	21.1

Note.—For effect of span, see Table No. 2. All bars were rectangular.

Four of these bars would be broken with the hammer falling 5 ins., which would barely break them. The resilience would be measured. The next four bars would be tested with the hammer falling 6 ins.; the next with a fall of 7 ins., etc. The results obtained will be seen in the last column of the table. It is evident that more experiments would have to be made to find the true relation between the height through which the hammer falls and the energy absorbed in the rupture. It is fair, however, to conclude in a general way, as has been stated, that a slight increase in the height will not materially affect the results obtained. There seems to be a tendency for the resilience to increase as the height is increased; but this tendency is all but concealed by variations from other causes.

Coming back to the regular order: Table No. 4 shows the effect of planing on the resilience of a cast-iron bar. The results shown are somewhat remarkable. The bar, after planing off the surface on all four sides, is much tougher than it was before. This difference cannot be due to any fault in the method of testing, as may be seen from a comparison of this table with Tables Nos. 2 and 3. The superiority of the planed bar is probably due to the lessening of the shrinkage strains when the surface of the rough casting is removed. It is possible that the same gain might be made by annealing the rough bar. The discovery of the great increase in resilience after planing might have been prophesied, perhaps, from studies heretofore made of the loss of strength due to shrinkage strains. This fact, however, has never before been demonstrated by actual impact tests, to the

TABLE No. 5.—Resilience of Cast-Iron Bars.

Effect of increasing initial fall of hammer.

Melt.	Experiment Nos.	Number of tests made.	Size of Bar.			Weight of bar, in pounds. W.	Initial fall of hammer, in inches. F.	Resilience per cubic inch, in inch-pounds. R_1.
			Span. L.	Depth. h.	Width. b.			
3........	156-159	4	24	1	2	13	7.0	11.4
	164-167	4	24	1	2	13	9.5	12.1
	160-163	4	24	1	2	13	12.0	12.5
3........	170-174	5	12	1	2	6.5	4.0	12.7
	180-183	4	12	1	2	6.5	6.5	13.0
	177-179	3	12	1	2	6.5	9.0	16.8
	175-176	2	12	1	2	6.5	12.0	15.2
4........	219-222	4	24	1	2	13	6.0	11.8
	223-226	4	24	1	2	13	7.5	11.6
	215-218	4	24	1	2	13	9.0	11.5
4*........	253-255	4	12	0.9	1.9	5.7	5.0	21.2
	249-252	4	12	0.9	1.9	5.7	6.0	19.1
	256-259	4	12	0.9	1.9	5.7	7.0	21.9
	260-263	4	12	0.9	1.9	5.7	8.0	22.3

* Planed.

Note.—All bars were rectangular.

author's knowledge. The great advantage of finishing castings exposed to shocks should be taken into account by designers of machinery.

Table No. 6 gives the results of tests of paving brick. The first tests of brick, made with the hammer, were unsuccessful on account of the great thickness of a brick compared with its length. The broken brick would wedge between the hammer and the opposing knife-edge, so that the hammer could not swing through. To remedy this, the author devised a knife-edge which would be immovable when struck squarely, but which would move freely by a side pressure. The form and dimensions of this device are shown in Fig. 13. As soon as the brick is broken, the knife edges are thrown outward and the hammer swings freely through. With the aid of these "free knife-edges" bricks were tested with good results.

Owing to the low resilience of a brick compared with its weight, it was found advisable to raise the hammer no higher than was necessary to break the brick. A higher drop usually showed a higher resilience. It is probable that the values given in Table No. 6 are higher than would be obtained could the error due to inertia be entirely eliminated. It is hardly safe to accept these results in comparing bricks, unless they be of the same dimensions.

TABLE No. 6.—RESILIENCE OF VITRIFIED PAVING BRICK.

All broken on a span of 7 ins.

Where made.	Number of lot.	Depth, in inches. h.	Width, in inches. b.	Weight of brick, in pounds. W.	Experiment Nos.	Number of tests.	Resilience per cubic inch, in inch-pounds. R_1.
Glen Carbon, Ill...	2	2.6	3.7	6.7	531-536	6	1.43
Galesburg, Ill.....	3	2.6	3.9	7.1	564-569	5	2 64
Kansas City, Mo...	4	2.5	3.8	6.8	539-544	5	1.00
Galesburg, Ill.....	5	2.6	4.0	6.9	545-550	6	1.54
Canton, O.........	6	2.5	3.9	6.8	551-557	6	2.09
Alton, Ill..........	7	2.5	3.8	6.5	558-563	6	1.25
Glen Carbon, Ill....	8	3.0	3.8	8.1	570-575	6	2.19
Athens, O..........	9	3.3	4.0	9.5	576-581	6	3.26*

* This high value is probably due, in part, to the greater weight.

Table No. 7 shows the results of a few tests of red brick. The comparative values obtained from soft and hard bricks are as might be expected. The familiar test of striking two bricks together in the hands is a crude impact test, and, in experienced hands, probably determines the comparative toughness of the brick with some accuracy.

Table No. 17 gives a comparison of the values obtained with different materials, tested in the manner described. They are classed as brittle materials because they can be tested in the same way as cast iron, and do not require special treatment, as do wrought iron and steel. The table gives a good rough idea of the comparative value of these materials under impact. The values given in the last column are the mean of several tests in each case. They should not be taken as typical, as the samples were taken from materials at hand and may not be truly representative.

TESTS OF TOUGH MATERIALS.

Having now dealt more or less effectively with the brittle materials, a class that presents greater difficulties must be considered. How, for example, shall the ultimate resilience of a sample of wrought iron be determined ? If an attempt is made to break a rectangular bar of soft iron, it will only be bent. To break such a bar successfully, it must first be nicked. A nicked bar can be broken, and the resilience to be overcome is but little more than that of the metal lying close to the nick.

TABLE No. 7.—RESILIENCE OF RED BRICK.

All broken on a span of 7 ins.

Kind of brick.	Number of lot.	Dimensions of Brick, in Inches.			Weight of brick, in pounds. W.	Experiment Nos.	Number of tests.	Resilience per cubic inch, in inch-pounds. R_1.
		l.	h.	b.				
Face brick..............	2	8.5	2·4	4.1	5.4	687–691	5	0.26
Common, hard burned.	3	8	2.2	3.9	5.1	692–695	4	0.30
Common, soft.........	5	8.5	2.2	4.2	5.2	708–713	6	0.10

For want of some better method, the author adopted the plan of using a nicked bar for testing soft iron and steel, and determining the ultimate resilience per square inch of cross-section at the nick. If the nick is deep enough to cause the bar to break off short, and is always

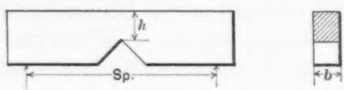


FIG. 7

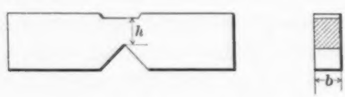


FIG. 8

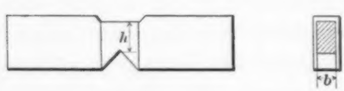


FIG. 9

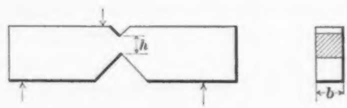


FIG. 10

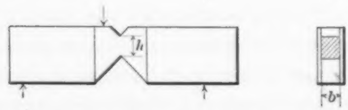


FIG. 11

of the same form, it would seem that the resilience should be in some degree proportional to the area of the reduced section. If, furthermore, the reduced section be always of the same depth, the resilience should be directly proportional to the area.

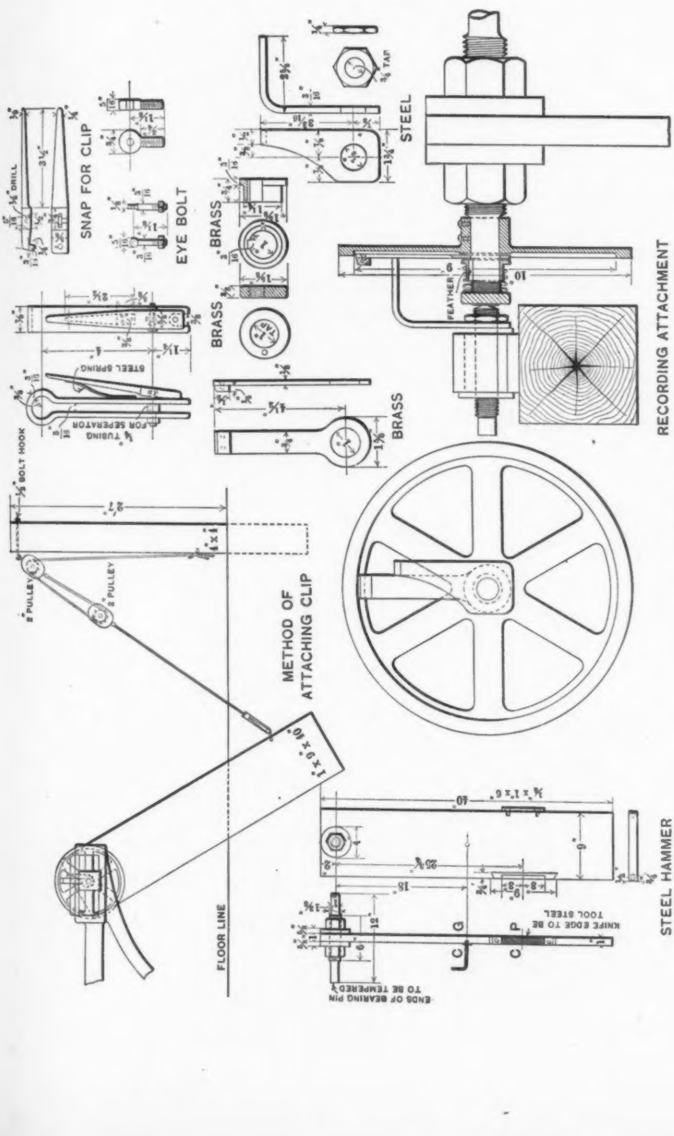

SNAP FOR CLIP
EYE BOLT
BRASS
BRASS
BRASS
STEEL
STEEL SPRING
FOR SEPERATOR
TUBING
BOLT HOOK
PULLEY
PULLEY
FEATHER
RECORDING ATTACHMENT
METHOD OF ATTACHING CLIP
FLOOR LINE
TOOL STEEL
KNIFE EDGE TO BE
ENDS OF BEARING PIN
TO BE TEMPERED
STEEL HAMMER

FIGURE 12.

TABLE No. 8.—Nicked Cast-Iron Bars.

Resilience per square inch.

Number of melt.	Experiment Nos.	Fig. No.*	Depth of section at nick, in inches. h.	Width of section at nick, in inches. b.	Number of tests made.	Resilience, in inch-pounds per square inch of section at nick. R_2.	Resilience, in inch-pounds per cubic inch of rectangular bars (rough) from same melt. R_1
3....	210-214	7	.5	1.0	5	49.5	11.4
3....	205-209	7	1.0	1.0	5	83.8	11.4
4....	272-275	9	.5	.9	4	81.6	11.8
4....	268-271	9	.75	.9	4	91.4	11.8
4....	264-267	9	1.0	.9	4	100.7	11.8

* Figure No. giving shape of nick (see Figs. 7 to 11).

N. B.—All bars 2 ins. x 1 in. All nicked bars broken edgewise, on 12-in. span. Weight of each bar about 6.4 lbs.

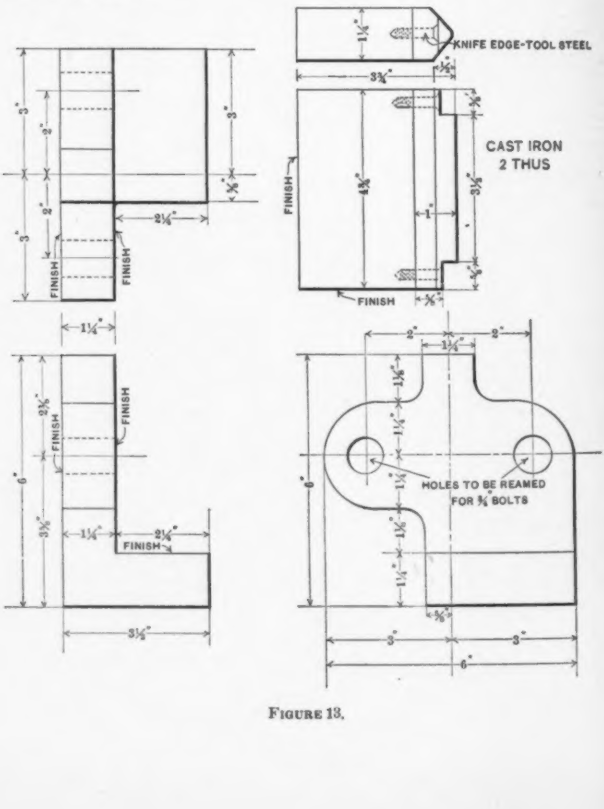


Figure 13.

TABLE No. 9.—Nicked Wooden Bars; Lot No. 3.

Resilience per square inch.

Experiments Nos. 313 to 375. All bars shaped as shown by Fig. 8, with depth of about ¾ in. at nicked section. Depth. 1¾ to 2 ins. at ends. Width of bars, ⅞ to 1¾ ins., when not shown in second column. Span, 8 ins. These tests were made without shims, to prevent denting.

Kind of Wood.	Width of section at nick, in inches. b.	Weight of bar, in pounds. W.	Number of tests made.	Resilience, in Inch-Pounds per Square Inch of Section at Nick. R_2. Maximum.	Minimum.	Average.
White pine	....	....	4	221	84	129
Ash	....	....	4	203	161	172
Cherry	.9	.38	4	299	118	216
Poplar	....	....	4	255	168	222
Red cedar, No. 1	1.0	.49	2	235	215	225
" " No. 2	1.7	.85	2	86	85	85
Gum	1.0	.44	4	299	....	247
Cypress, No. 1	1.7	.52	2	....	225	250
" No. 2	.9	.26	2	87	69	78
Chestnut	1.1	.44	6	432	199	306
Yellow pine	....	....	4	447	229	322
Black walnut	.9	.44	4	420	235	328
Maple	.9	.43	3	574	432	516
White oak	....	....	4	650	438	546
Oak, No. 2	....	....	4	500	....	419
Locust*	1.0	.56	6	690	566	633
Hickory*	1.1	.73	6	1 418	1 118	....

* The results in these remarkably tough woods are not strictly comparable with the others, on account of tearing out of the extreme fiber.

Figs. 7 to 11 show the different forms of nick that were used in the experiments. Each form of nick is designated by a figure number, so that it may be referred to in the tables. The order of these figures shows the results of the experience gained in these tests.

The first timber tests were made with bars like Fig. 7. The form shown in Fig. 8 was then tried in order to reduce the chances of longitudinal splitting. In Fig. 9, the section is diminished by planing the sides. Fig. 10 was found to give better results with very tough wood or metal. Fig. 11 is the same as Fig. 10, but with the section reduced as in Fig. 9. In the last two forms, the hammer strikes the bar at the side of the smaller nick.

Table No. 8 shows the results of nicked tests made with cast-iron. The values given in the last column show that the metal was all of equal toughness. The observed values, given in the column next

TABLE No. 10.—Nicked White Oak Bars.

Effect of shields or shims at knife-edges.

All bars of straight-grained white oak of same quality. Bars nicked as shown in Fig. 10. Depth of section at nick (h) = 0.8 ins. Width of section (b) = 1.7 ins. Size of bar at ends = 1.75 ins. square. Weight of bar = 0.88 lb. Span, 8 ins.

	Experiment Nos.	Number of tests.	Resilience R_2. Maximum.	Minimum.	Average.
With shims.......	450–455	6	430	301	343
Without shims...	456–461	6	505	278	410

to the last, indicate that the resilience per square inch of section is not constant for varying depths of section.

Table No. 9 shows the results of tests with different kinds of wood. The resilience values shown by this table are probably somewhat high on account of loss by denting the wood. Table No. 10 shows some tests made to learn how much loss of energy was occasioned by denting. From these results it would appear that the loss in this way was considerable, and that the wood should always be protected by shields or shims, at the knife-edges. The shims used were thin strips of tempered steel about ½ in. wide. They were laid flatwise between the knife-edge and the specimen. All the later experiments were made with the specimens protected from the knife-edges in this way.

Table No. 11 shows the results of tests made to determine the effect of increasing the depth of the nicked section. The results indicate that the resilience of a nicked bar is not directly proportional to the area of the nicked section. The variation is in the same direction as it was in the cast-iron bars recorded in Table No. 8.

The nick shown by Fig. 10, which was used in the tests shown in Tables Nos. 10, 11 and 12, was found to be the most satisfactory form for tests of wood. With this nick there is seldom any longitudinal splitting, which would destroy the value of the test. Table No. 12 shows tests of white and yellow pine and white oak, made with this form of nick. Shims were used in these tests, so that they may be considered as made in a more approved manner than the tests of Table No. 9. It is interesting to compare these timber tests with those made by Professor Thurston (see Table No. 21).

TABLE No. 11.—Nicked Yellow Pine Bars.

Resilience per square inch.

All bars of same lot of straight grain lumber. Bars nicked as shown in Fig. 10. Width of section (b) = $1\frac{1}{2}$ ins. Size of bar at ends 2 x $1\frac{1}{2}$ ins. Weight of bar = 0.75 lbs. Bar protected by steel shims at knife-edges. Span, 8 ins.

Depth of section at nick. h.	Experiment Nos.	Number of tests.	Resilience, in Inch-Pounds per Square Inch of Section. R_2.		
			Maximum.	Minimum.	Average.
.66	523-530	8	410	124	312
.88	496-503	8	525	211	447

TABLE No. 12.—Nicked Wooden Bars; Lot No. 4.

Resilience per square inch.

All bars $1\frac{3}{4}$ to 2 ins. deep at ends. All bars nicked as shown in Fig. 10. Bars protected by shims. Span, 8 ins.

Kind of Wood.	Depth of section at nick. h.	Width of beam, in inches. b.	Weight of beam, in pounds. W.	Number of tests made.	Resilience, in Inch-Pounds per Square Inch of Section. R_2.		
					Maximum.	Minimum.	Average.
White pine......	.88	.83	.35	7	223	90	161
Yellow pine.....	.66	1.5	.75	8	410	124	312
White oak......	.80	1.7	.88	6	430	301	343

TABLE No. 13.—Nicked Bronze Bars.

Resilience per square inch.

Bronze containing 85% of copper. All bars from same melt (lot No. 2), and 2 ins. x $\frac{1}{2}$ in. at ends. All broken edgewise on 12 ins. span.

Experiment Nos.	Figure number.	Depth of section at nick, in inches. h.	Width of section at nick, in inches. b.	Weight of bar, in pounds. W.	Number of tests made.	Resilience, in Inch-Pounds per Square Inch of Section at Nick. R_2.		
						Maximum.	Minimum.	Average.
394-399..	7	1.00	.50	4.22	3	1 305	1 192	1 252
		.50	.50	4.13	3	1 302	884	1 087
473-478..	9	1.00	.38	4.31	3	1 205	1 087	1 147
		.32	.38	4.00	3	769	581	673

Note.—Ultimate strength, 27 730 lbs. per square inch. 6.9% elongation in 8 ins. Tensile resilience by gradual load, 1 573 in.-lbs. per cubic inch.

TABLE No. 14.—Nicked Plow-Steel Bars.

Resilience by impact and by gradual load.

All bars nicked as shown in Fig. 7, and broken edgewise on a span of 12 ins. All bars 2 ins. x ¼ in. Weight of one bar = 1.6 lbs.

By Impact.			By Gradual Load.	
Depth of section at nick, in inches. h.	Number of tests made.	Resilience, in inch-pounds per square inch of section at nick. R_2.	Number of tests made.	Resilience, in inch-pounds per square inch of section at nick. R_3
.50	4	2 115	4	1 527
.75	4	1 625	3	1 133
.75	..	.....	1	1 460
.25	4	1 913	..	.....

Note.—All from lot No. 1. Ultimate tensile strength, 83 720 lbs. per square inch. Elongation, 20.3% in 7⅝ ins. Ultimate tensile resilience by stress diagram, 15 000 in.-lbs. per cubic inch, gradual load.

Table No. 13 shows twelve experiments with bronze. Here, again, it will be noticed that the resilience per square inch increases with the depth h, as it did in the case of cast-iron and wood.

Table No. 14 shows a comparison of impact and gradual loading on nicked bars of plow-steel. The gradual load tests were made in an ordinary transverse testing machine; the loads and corresponding deflections were observed and plotted, and the resilience was taken from the diagram. It will be noticed that the resilience by impact is about one-third greater than the resilience by gradual load. The difference is nearly as great as was observed in rectangular bars of cast iron (see Table No. 1). Table No. 14 shows also that the resilience per square inch does not increase with a greater depth of section, as was observed in nicked bars of cast-iron, wood and bronze. In the plow-steel tests it is found that the greatest depth gives the least unit resilience, quite the opposite of what might have been expected.

Table No. 15 shows a number of experiments with steel and iron. In making these experiments it was found that with very tough metal the bar should be nicked on both edges, to insure a clean break and uniform results. Some of the lots of steel were tested for tensile strength and elongation. The results of these tests are given in Table No. 15.

TABLE No. 15.—Nicked Iron and Steel Bars.

Resilience per square inch.

Bars nicked as shown by Fig. 10. Depth of section at nick, in inches, $(h) = 0.25$.

Metal.	Lot number.	Number of melt.	Number of tests made.	Depth and thickness of bar before nicking, in inches.	Width of section at nick, in inches. b.	Resilience, in inch-pounds per square inch of section, at nick. R_2.	Ultimate tensile strength, in pounds per square inch.	Percentages of elongation in 8 ins.
Iron, Norway........	2	....	4	$1\frac{3}{4} \times \frac{1}{4}$	.25	7 200	41 500	28.2
" Tenn. Com....	3	....	6	$1\frac{1}{2} \times \frac{1}{4}$	.25	2 308	55 000	21.2
" " charcoal.	4	....	6	$1\frac{5}{8} \times \frac{1}{4}$	.25	3 560	52 500	27.5
Soft steel...........	3	....	4	$1\frac{1}{2} \times \frac{3}{4}$	.75	1 285	......	....
" "	6	743	3	$1\frac{5}{8} \times \frac{1}{4}$	.27	3 385	60 900	26.1
" "	6	743	2	$1\frac{5}{8} \times \frac{5}{16}$	.32	5 828	53 750	30.3
" "	6	743	3	$1\frac{5}{8} \times \frac{3}{8}$	.39	5 415	53 300	32.4
" "	6	743	2	$1\frac{5}{8} \times \frac{7}{16}$	.45	3 886	54 800	29.6
" "	6	743	3	$1\frac{5}{8} \times \frac{1}{2}$	.50	4 919	52 250	33.1
" "	6	749	3	$1\frac{5}{8} \times \frac{1}{4}$	.27	3 448	63 100	27.0
" "	6	749	3	$1\frac{5}{8} \times \frac{5}{16}$	.32	4 709	61 250	23.9
" "	6	749	3	$1\frac{5}{8} \times \frac{3}{8}$	.39	4 366	56 100	31.6
" "	6	749	3	$1\frac{5}{8} \times \frac{7}{16}$	.45	4 065	57 000	31.5
" "	6	749	2	$1\frac{5}{8} \times \frac{1}{2}$	.50	1 821	58 600	25.8
" "	6	757	3	$1\frac{5}{8} \times \frac{1}{4}$	.27	4 836	60 600	25.4
" "	6	757	2	$1\frac{5}{8} \times \frac{5}{16}$	.32	6 036	56 900	30.5
" "	6	757	3	$1\frac{5}{8} \times \frac{3}{8}$	.39	4 997	56 000	26.2
" "	6	757	2	$1\frac{5}{8} \times \frac{7}{16}$	.45	2 743	55 600	27.7
" "	6	757	3	$1\frac{5}{8} \times \frac{1}{2}$	.50	2 981	57 600	27.5
" "	7	794	3	$1\frac{1}{2} \times \frac{1}{2}$	.50	1 523	61 800	25.1
" "	7	806	3	$1\frac{1}{2} \times \frac{3}{8}$	.39	4 416	58 900	29.0
" "	9	918	3	$1\frac{3}{4} \times \frac{1}{2}$	.52	3 810	52 720	32.4
Medium steel.......	3	....	3	$2 \times \frac{3}{4}$	.75	773	......	....
" "	6	B	1	$1\frac{5}{8} \times \frac{1}{2}$	.49	1 106	......	....
" "	6	C	1	$1\frac{5}{8} \times \frac{5}{8}$	.61	1 769	......	....
" "	6	D	1	$1\frac{5}{8} \times \frac{1}{2}$	.47	5 611	......	....
" "	6	G	1	$1\frac{5}{8} \times \frac{1}{2}$	.50	1 064	......	....
" "	6	H	1	$1\frac{5}{8} \times \frac{1}{2}$	.47	4 822	......	....
Nickel "	1	....	4	$2 \times \frac{1}{4}$	.25	2 600	72 680	27.5
Fluid comp. steel....	1	....	4	$2 \times \frac{1}{4}$	.25	3 300	91 260	18.9
Cast Steel	2	....	2	$2 \times \frac{3}{8}$	.37	1 770	......	....
" "	2	....	2	$2 \times \frac{1}{4}$	.25	1 709	......	....

Table No. 16 gives the records of tests made with bars of aluminum. The metal was of the kind used in making bicycle frames. An analysis showed 98.05% of aluminum. A tensile test showed 16 750 to 19 970 lbs. per square inch ultimate strength, and $1\frac{1}{2}$ to $3\frac{1}{2}$% elongation, in 8 ins. The specific gravity of the metal was 2.764. In these tests a greater unit resilience with a greater depth of section may again be observed.

Table No. 18 gives a comparison of the tests made with different metals. The values cannot be taken as typical. The numbers given

TABLE No. 16.—Nicked Aluminum Bars.

Resilience per square inch.

All bars 8 ins. long between supports. Experiments Nos. 740-762.

Depth and width of bar at ends, in inches.	Fig. No.	Size of Section at Nick, in Inches. Depth. h.	Width. b.	Weight of bar, in pounds. W.	Number of tests made.	Resilience, in inch-pounds per square inch of section at nick. R_2.
1¼ x 1¼..............	10	.25	1.25	1.44	4	468
	10	.37	1.25	1.45	4	600
	11	.37	.75	1.41	3	513
2 x 1¼................	10	.25	1.25	2.06	4	530
	10	.50	1.25	2.13	4	579
	11	.50	.75	2.07	3	519

Note.—Ultimate tensile strength, 16 750 to 19 970 lbs. per square inch Elongation, 1¼ to 3⅛% in 8 ins. Ultimate tensile resilience by stress diagram, 15 000 in.-lbs. per cubic inch, gradual load.

TABLE No. 17.—Resilience of Brittle Materials.

Resilience, in inch-pounds per cubic inch. All tests made with rectangular beams, struck in the center and broken by a single blow.

Material.	Resilience. R_1. Max.	Min.	Av.	Material.	Resilience. R_1. Max.	Min.	Av.
Cast-iron, rough.........	18	10	11.5	Common brick, soft.....	......	......	.10
" " planed.........	22	19	21	Fire "	......	......	.44
Vitrified paving brick...	3	1	1.6	Terra cotta, red.........	......	......	.33
Face brick, red..........	......	......	.26	"Granitoid"*...........	.30	.15	.20
Common brick, hard....	......	......	.30				

* A composition of Portland cement and crushed granite, much used for sidewalks.

Table No. 18.—Resilience of Tough Materials.

Resilience, in inch-pounds per square inch of section at nick. All tests made with rectangular beams, nicked at the center and broken by a single blow. Fig. No. 10, $h = 0.25$ in.

Material.	Resilience. R_2. Max.	Min.	Av.	Material.	Resilience. R_2. Max.	Min.	Av.
Aluminum...............	530	468	500	Soft-steel................	6 000	1 300	3 000
Wrought-iron............	7 200	2 300	2 000	Cast-steel................	1 770	1 709	......
Medium-steel............	5 600	770	2 000				

TABLE No. 19.—IMPACT TEST.

ST. LOUIS, February 24, 1897.

Office of Water-Works Extension. Specimen of cast iron taken from Shickle & Harrison. Specials—Pump Main No. 8. Tested for cross-breaking resilience, with results herewith appended. Lot No. 6.

Experiment No.	Bar No.	Initial fall of hammer, in inches. F.	Rise after blow, in inches. S.	Correction for friction, in inches. C_1	Length between supports, in inches. L.	Depth of beam. h.	Width of beam. b.	Volume of bar, in cubic inches. $V=Lhb$.	Weight of bar in pounds. W.	Correction for inertia of bar, in inches. $C_2 = .011$ W. S.	Effective fall of hammer. $H=F-(S+C_1+C_2)$.	Total resilience, in inch-pounds. $R = 103$ H	Resilience per cubic inch, in inch-pounds. $R_1 = \frac{103 \text{ H}}{\text{V}}$	REMARKS.
582	1	6	3.24	0.17	12	1.05	2.07	26.082	7.75	.28	2.31	237.93	9.12	
583	2	4	0.64	0.13	12	1.09	2.02	26.420	....	.05	3.18	327.54	12.40	
584	3	4	0.85	0.13	12	1.05	2.05	25.830	....	.07	2.95	303.85	11.76	
586	4	4	1.38	0.13	12	1.02	2.05	25.092	....	.12	2.37	244.11	9.73	Small flaws on tension and comp. side.
587	5	4	0.81	0.13	12	1.04	2.00	24.960	....	.07	2.99	307.97	12 34	
588	6	4	1.55	0.14	12	1.00	2.03	24.360	....	.13	2.18	224.54	9.22	
												Av.....	10.76	

TABLE No. 20.—RESILIENCE OF BEAMS.

R = Resilience, in inch-pounds of a beam 1 in. square and 12 ins. between supports.

Kind of material.	Value.	Kind of material.	Value.
Cast-iron	81	Oak, English	78.4
Slate	3.2	" Canada	71.5
York paving	0.96	Pine, pitch	70.7
Ash	127.6	" red	58.7
Cedar	100.0		

NOTE.—The above values were taken from Table No. 67 of Box on "Strength of Materials."

TABLE No. 21.—RELATIVE TORSIONAL RESILIENCE.

Kind of wood.	Value.	Kind of wood.	Value
White pine	1.00	Yellow pine	3.87
Spruce	1.50	Black walnut	3.95
Red cedar	1.61	Locust	5.80
Spanish mahogany	1.65	Oak	6.60
Ash	2.25	Hickory	6.90
Chestnut	2.40		

NOTE.—The above table was taken from Thurston's "Materials of Engineering." These tests were made with gradual load.

in the last column for wrought iron and soft and medium steel are thought to be fair values for an average grade of metal. In low-grade steels, or steels low in carbon, it is a commonly accepted theory that a high percentage of phosphorus makes steel brittle under impact.* It may be from such a cause that some of the steel tested gave such low results. It may be, on the other hand, more a question of the temperature at which the metal was finished in the rolls.

Tables Nos. 20 and 21 were taken from well-known authorities, and are given for comparison with the results of the other experiments. Both of these tables present values of resilience by gradual loading.

*Johnson's "Materials of Construction," pp. 166 and 167.

CONCLUSIONS.

The conclusions are: *First,* in the case of brittle materials, definite values for resilience may be obtained.

Second, in the case of tough materials, like wrought iron, definite relative values for resilience of materials of the same class may be obtained by the use of a test bar of standard form and size.

This latter conclusion indicates that it may be specified that steel shall show a certain ultimate resilience per square inch, with a given form of nicked test bar. Should this requirement prove satisfactory in practice, it may eventually be possible to dispense with chemical tests of steel for structural purposes.

It may also be concluded from the tests that the resilience of cast-iron bars is greatly increased by planing.

One more important deduction may be made from the tests, and that is, that metals show a higher ultimate resilience under impact than they do under gradually applied loads.

When the proper values of resilience under impact have been determined for structural materials, designers will be able to act with more intelligence in planning structures exposed to live loads and to shocks. They will be able to substitute iron or stone for wood in certain cases with greater assurance of safety. The study of resilience will also lead to better designing in other ways. Useless material in a structure or member will generally decrease the resilience, which fact is already well known but frequently lost sight of. The general use of resilience tests would serve to keep such facts in mind, and make them more commonly understood.

It is with the idea of encouraging the practical use of impact tests that the results of these experiments are offered to the Society.

DISCUSSION.

Mr. Buck. L. L. Buck, M. Am. Soc. C. E.—While the New York and Brooklyn bridge was being built, the speaker saw some interesting experiments on resilience. A wire about 100 ft. in length was suspended from the land span on the New York side, and on the lower end there was a nut and a washer. Above the washer, and sliding on the wire, there was a weight of about 50 lbs. The weight was first raised about 2 ft. and allowed to drop. It was then dropped from a height of 4 ft., then 6 ft., etc., the distance being gradually increased for each drop. The wire was broken by the weight falling from a height of 36 ft. The elongation of the wire before it broke was remarkable.

A rod, about 94 ft. long and 1 in. in diameter, to the lower end of which was attached a wire 6 ft. long, was used in another experiment. At the lower end of the wire there was a nut and a washer, and the same weight was made to slip over the rod. The weight was dropped from a height of 1 ft., then from a height of 2 ft., etc. The wire, although cut from the same piece as in the first experiment, was broken by the falling of the weight from a height of 6 ft. This showed the effect of the length of time taken in arresting the motion of the falling weight. When the length of the wire was only 6 ft. there was very little elongation, and it was broken apparently very easily. This can be shown by using a rubber strap to arrest the motion of a weight which would on falling the same distance break a wire considerably stronger than the strap.

In the experiments mentioned the elongations of the wire under the different falls were not measured. The wire was of No. 7 steel, having a tensile strength of 160 000 lbs. per square inch. The long wire broke some 6 or 8 ft. from the bottom ; the short wire about 2 ft. from the bottom.

Mr. Mayer. Joseph Mayer, M. Am. Soc. C. E.—The resilience of a material is the quantity of work consumed per pound before breaking, if tested as a prismatic body.

Prismatic bodies of a given material consume a certain amount of work per pound which is independent of the shape and size of the piece.

If nicked pieces are used, the same material will absorb, before breaking, a different amount of work per pound, according to the size and shape of the nick and the size and shape of the piece. The amount of work absorbed per pound, of a given material is not a constant, but depends on various factors independent of the quality of the material. It is therefore entirely improper to call the amount of work absorbed under such conditions its resilience.

Unless the term resilience means the amount of work per pound consumed by prismatic bodies before breaking, it has no definite mean-

ing at all, and each experimenter will obtain a different resilience for the same material according to the shape of the piece tested; and confusion reigns supreme and brings discredit on all the tests and on the whole idea of resilience. Mr. Mayer.

J. B. Johnson, M. Am. Soc. C. E., has made a number of valuable tests,* in which the resilience of cast iron was measured by gradually applied loads.

These tests do away with the inaccuracies unavoidable in tests by blows, because in the latter an unknown amount of the work consumed is absorbed by the yielding of supports, the inertia of the test piece, and the development of heat.

These tests by gradually applied loads give results similar to those by blows, and they could be applied to soft materials without nicking them, so as to obtain their real resilience.

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* *Transactions*, Vol. xxii, p. 91.

CORRESPONDENCE.

Mr. Christie. JAMES CHRISTIE, M. Am. Soc. C. E.—A determination of resilience, especially if obtained by impact tests, would supply desirable knowledge of the practical value of materials. When the material is susceptible to fracture, and has no well-defined elastic limit, the ultimate resilience alone can be depended upon ; but in ductile materials, or those that do not fracture readily, a determination of the elastic resilience would be more useful. The author might obtain this in his impact machine by introducing another pendulum, bearing on the reverse side of the specimen; the energy conveyed to this pendulum, through the deflection of the specimen, being used as a basis for computations of elastic resilience.

The results obtained from nicked specimens are of doubtful utility. Possibly in wood or similar material, which is formed by an assemblage of strands or fibers, the resistance of the nicked specimen may bear some constant ratio to that of a specimen with parallel sides, but this is not true in the case of a material of a crystalline character. The well-known weakness of a nicked bar of high-grade steel is confirmed by the results obtained by the author, which place tool-steel below the hard woods in resilience. The theory of elasticity indicates that when deflection occurs in such nicked specimens, the stresses at the interior angle are infinite, or that destruction has begun at the lowest possible stress. Therefore, nicking the specimen is only partially destroying the material, in order to insure rupture in material that otherwise would not break by a bending process.

Mr. Meem. J. C. MEEM, Assoc. M. Am. Soc. C. E.—There are one or two points in this interesting paper concerning which the writer begs to offer the following in the line of suggestion or of asking for more information. In Tables Nos. 1 and 14 the author refers to the discrepancies noted between the resilience of metals broken by impact and by gradual loading. It appears to the writer that this discrepancy may be explained by the fact that the difference between the initial fall and rise of the hammers does not seem to be correctly expressed in the formula $R_1 = 103 \frac{[F - (S + C_1)]}{L\,h\,b}$ and that it should rather be $R_1 =$

$$103 \frac{\left(\frac{F^2}{a} - \left\{ \frac{S^2}{a_1} + C \right\}\right)}{L\,h\,b}$$

in which a and a_1 are the arcs, respectively, through which the hammer falls and rises, and F and S are the actual fall and rise, as in the first formula, *i.e.*, the versed sines of the arcs a and a_1; and, as it follows always that a_1 is larger with respect to S than a with respect to F, it will be found that the impact results will probably be reduced in any case by not more than $\frac{1}{3}$ or $\frac{1}{2}$. The

author's formula may perhaps embody this without expressing it in detail, but if it does not, it may account, as stated, for the discrepancy. Mr. Meem.

The author proves that it is necessary to know only the weight of the hammer and its relative rise and fall, and that an increase or diminution of this fall does not materially affect the result. This is especially interesting as doing away with the necessity for further consideration of the force and velocity of impact.

It is further borne out by the fact that a gradually applied load gives relatively the same results as one by impact.

It is instructive also to note that the length being the same, the resilience is the same for a piece broken along the breadth b as for one broken along the depth d; and that an increase of length proportionally increases the ultimate resilience. Both of these conclusions are borne out by an inspection of the theoretical formulas for resilience under a gradual load. As some of the author's results are expressed in terms of resilience per cubic inch, and others per square inch, the writer ventures to suggest that it might be well to express them always in terms of resilience per square inch. For it would seem to convey a more practical idea to say that the resilience of an inch bar was twice as great per square inch for a length of 24 ins. as for a length of 12 ins., than to say that the resilience per cubic inch was the same in each case; *i.e.*, it would seem better to express the variable (resilience per square inch) in terms of the variable (length). This point may likewise have been considered by the author, and discarded for good reasons in the valuable paper he has contributed to the opening of an apparently new field for the investigation of a very interesting subject.

J. B. Johnson, M. Am. Soc. C. E.—This paper is a substantial contribution to the literature on the strength of materials. The machine described is the first that has come to the notice of the writer, which will indicate the true shock-resistance of any engineering material. The theory of the machine is very simple and natural, and it is therefore the more remarkable that it should not have found an earlier embodiment. There is no portion of the vast field of testing the strength of materials which has been so grossly mismanaged and misunderstood as this matter of testing resistance to shock. As the writer has repeatedly asserted elsewhere, tests of shock resistance by repeated blows give no absolute data which can be used for comparative purposes. Only when all the conditions of the test and test-specimen are exactly duplicated can any comparison be instituted, and then only with the greatest caution and the most intelligent discrimination. The author's results, however, are absolute in their character, especially on brittle materials, and since it is only with such materials that engineers are especially concerned regarding the resistance to shock, his apparatus is all that practice really demands. Mr. Johnson.

Mr. Johnson. The paper shows the great necessity there is for a single word denoting resistance to shock. The author, in the absence of such a word, follows some other writers by using the term resilience, or total resilience, as indicating this property ; but there is no doubt that this is a misuse of the term. It has hitherto been restricted by careful writers, and by the highest authorities, to that definition given by the Century Dictionary (quoting Thomson and Tait), this being also the original meaning of the term as used by Young in 1807. The term resilience should, therefore, be made to mean only the energy given back by the body in returning to an unstressed condition. Within the elastic limit this is sensibly the same as the energy absorbed by the body in deforming it. If the return path (on a stress diagram) were identical with the deforming path, these two would be precisely equal, but as a matter of fact this return path (on the load coördinate) is always a little below the deforming path, the difference representing the small amount of heat generated and dissipated, even in elastic deformation. Beyond the elastic limit the resilience proper becomes a very small part of the deforming energy absorbed, so that two terms are needed, one indicating the energy put into the body in deforming it and the other the energy given back by the body in the act of recovery. The latter only should be called resilience. The former may be called resistance to shock, or shock-resistance, but in the opinion of the writer it should not be called resilience.

In the absence of such a machine as the author here describes the writer has been accustomed to determine shock resistance from the total area of the static stress diagram. That this gave too small a result he also knew, since it has been shown that for equal deformations, made statically and by impact, the resistance, or stress, is very much greater under a quick action than under a slow one, and hence the impact stress diagram, if it could be obtained, would be very much larger than the static diagram. Thus, for soft iron wire it has been shown that the actual resistance to shock is some 30% greater than would be inferred from a static stress-diagram.* For brittle materials it has been supposed there would be less difference. The author shows, however (Table No. 1), that there is at least this difference in the case of cast iron. In other words, the time element does effect the ratio of stress to deformation with brittle materials the same as with ductile materials. It follows, therefore, that a greater actual shock-resistance may always be expected than would be computed from static stress-diagrams, this excess being, perhaps, from one-third to one-half the computed shock-resistance. This in itself is a very important discovery.

The superior resistance of the planed bars (Table No. 4) is doubtless due, mostly, to the removal of the rough exterior rather than to the

* "*Materials of Construction*," p. 79.

relieving of internal stress. Mr. W. J. Keep has just shown* that a similar increase of strength under a static test results from the smoothing and peneing action of the innumerable blows received in a rattler. He undertakes to show, and apparently succeeds in showing, that this increase in strength is but slightly due to the shocks received [as had been proved (?) by Outerbridge in 1895], and that it is almost wholly due to the smoothing down of the rough exterior. It has long been known that test specimens show an increase of strength due to such smoothing away of all irregularities, even though these be very small, so that it is now common to require test specimens to be finished with a fine file, and, perhaps, polished, rather than to take them directly from the lathe or planer. Very small indentations furnish favorable conditions for the starting of a crack, or permanent deformation, when these would be considerably delayed without such starting points. Mr. Johnson.

The necessity of rigid supports in shock tests has been well brought out in the paper, and the author has evidently very successfully mastered this problem in his design.

It may still be doubted whether or not ductile or tough materials can be successfully tested on such a machine. If the author would try the experiment of varying the sharpness of the base of the notch at the center, as shown in Figs. 7 to 11, he would find that the slightest change here makes a great difference in the result. These results also would seem to have no absolute meaning, and comparisons could only be instituted between specimens which were identical in size and shape in every particular. "Energy absorbed per square inch of cross-section" is a meaningless phrase, since no energy can be absorbed on a true mathematical plane or section. Some length dimension must be included to give a volume on which the energy spends itself, but what this length dimension is, in the case of nicked bars, cannot be determined. It would seem, therefore, that the only true field for such tests as here described is with brittle materials. For these the author seems to be the first to show how an absolute shock-resistance modulus, which is characteristic of the material and independent of the form and dimensions of the specimen, can be obtained, and it is this which gives to the paper a very great significance and value.

S. Bent Russell, M. Am. Soc. C. E.—The first point raised by Mr. Meem (a question of formulas) does not seem to be well taken, as the following illustration will show: Mr. Russell.

Assume a pendulum weighing 100 lbs., swinging in a vacuum on frictionless supports so that its center of gravity rises and falls through a vertical height of 1 ft. The energy contained in the pendulum will be 100 ft.-lbs. at any instant, whether taken at its highest point, when it has no velocity, or at its lowest point, when it has the greatest velocity, or at any intermediate point.

* In a paper before the Am. Soc. Mech. Engrs., New York meeting, December, 1897.

Mr. Russell. Having determined the energy of the pendulum to be 100 ft.-lbs., it must be capable of doing 100 ft.-lbs. of work. Now interpose a test-bar at any point in the path of the pendulum, where it will be broken. After the bar is broken by the pendulum it is found that the latter is still swinging back and forth, but that it now swings through a smaller arc. Suppose that, on measuring, the center of gravity is now found to rise and fall through a vertical height of $\frac{1}{2}$ ft. The pendulum now contains but 50 ft.-lbs. of energy and hence the difference, or 50 ft.-lbs., has been absorbed in breaking the test bar, as is known from the law of the conservation of energy. It is not necessary to know the position of the test bar or the length of the arcs, or even the length of the pendulum.

The vertical height through which the hammer is raised determines the energy in it as soon as it is released. Hence, in the testing machine described (where the hammer weighs 103 lbs.) 103 F is the energy before striking, and 103 S is the energy after rupture. Add to the latter a small quantity, or what is believed to have been lost in friction, and take 103 $(S + C)$ as the true energy after the rupture of the bar. The difference between these values, or 103 $[F - (S + C)]$, must correctly express the value of the energy absorbed in rupturing the specimen.

In reference to the point made by Professor Johnson on the resilience of planed cast-iron bars, the author cannot agree with him in thinking that the experiments of Mr. Keep are conclusive in the matter, and would still incline to the opinion that it is largely a question of shrinkage strains.

There is another statement made by Professor Johnson to which the author cannot fully subscribe, viz.: "It is only with such (brittle) materials that engineers are especially concerned regarding the resistance to shock." Engineers are concerned with the resistance to shock of all structural materials, and it may certainly be allowed that they are especially concerned with the resistance to shock of the higher grades of structural steel. The greater the strength of steel, the greater the danger of low resistance to shock, hence the more complete the knowledge of the shock resistance of the metal, the higher the strength that can be used with assured safety and the more economical the design. If impact tests have been found a practical necessity in the case of rails, railway axles and cast-steel drawbars, it can scarcely be denied that a knowledge of the resistance to shock of tough material is eminently desirable.

Referring to Mr. Meem's last point, as to expressing resilience in terms of its value per square inch, it may be said that there would seem to be no advantage in giving the resilience of rectangular bars in terms of the area of the section for a stated length. In the case of nicked bars the use of the term resilience per square inch is open to objection and is only excusable where the width and depth are nearly uniform for all the

sections to be compared, and where the material is of the same character, so that the field of distortion may be presumed to be the same in all sections. Even under these conditions the expression should be regarded as a temporary expedient, so that the true conditions of each experiment are not lost sight of. In using this expedient it is assumed that the unknown length dimension is the same in all bars to be compared. Mr. Russell.

In discussing this point Professor Johnson remarks that resilience per square inch "would seem to have no absolute meaning." Granting this, it may be in order to note that "percentage of elongation" has likewise no absolute meaning. The length measured must be given, or no definite knowledge is conveyed. Given the percentage of elongation in 8 ins. of a sample of steel, and who can say what the percentage of elongation will be in a length of 2 ins. or in a length of 8 ft.? And yet it is the common practice to give the elongation in percentage, stating the length measured. In something the same way resilience per square inch means nothing unless the form and dimensions of the bar are given, but it seems easier to make comparisons if the results are reduced to a common area.

Mr. Christie remarks that "The results obtained from nicked specimens are of doubtful utility," and in this position is sustained by Messrs. Mayer and Johnson. In considering this point it is, perhaps, in order to note that in all physical tests of material there is more or less difficulty in obtaining results that are "characteristic of the material and independent of the form and dimensions of the specimen." For instance, in the case of cement, experimenters have been working for years to obtain such results, and with but indifferent success. Therefore, we need not be discouraged if only comparative values can be obtained in the case of ultimate resilience of steel.

It is also in order to note that in actual practice structural material is not always used in prismatic forms subject to uniform stress.

Wherever two members are joined together, there are changes of section more or less abrupt. At every seam in a boiler shell a somewhat abrupt reduction of section is made by the row of rivet holes. The screw thread on a bolt causes a nicked section. In timber construction the pieces have sharp re-entrant angles where they are framed together.

Keeping these points in mind and admitting that the nicked tests are merely comparative and are so only when the specimens are identical in size and shape in every particular, it seems fair to conclude that tests of nicked specimens may yet prove of some practical value, in the absence of a better method of determining the toughness of ductile materials under shock. The value of nicked tests could best be determined with a suitable testing machine located in a steel mill, where specimens could be obtained of any desired thickness and composition and worked at any desired temperature.

Mr. Russell. Professor Johnson's objections to the use which has been made of the word resilience in the paper are doubtless well taken. The term shock-resistance, however, does not appear to be free from objection. For example, the title of Table No. 1 is "Resilience by Impact and by Gradual Load." Shock-resistance by gradual load would be an inconsistent expression, hence the term shock-resistance cannot be substituted here to convey the idea in mind. It would be desirable, then, to find some expression for energy absorbed which would avoid the use of the word shock.